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Art. VI.—*On Grooved, Pitted and Miniature Pedestal Rocks at Lake Goongarrie, Western Australia.*

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(With Plates XII., XIII.)

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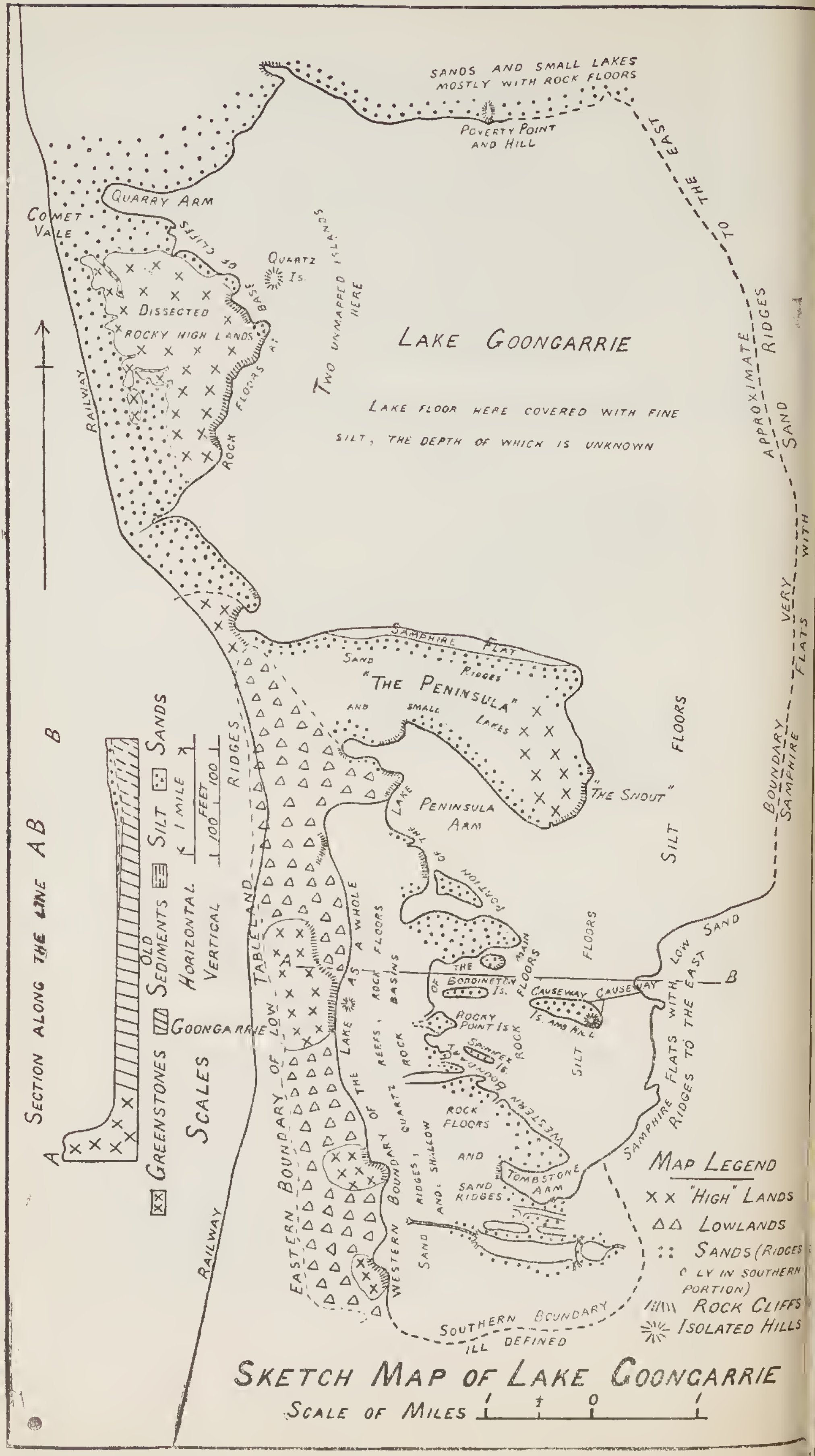
Contents.

I. Introduction.

Lake Goongarrie is a "dry" lake or playa in sub-arid south-central Western Australia. It lies north of Kalgoorlie and just to the east of the railway line from Kalgoorlie to Leonora, and extends northwards from Goongarrie to Comet Vale. It is situated on the Great Plateau of Western Australia, which in the district referred to is about 1200 feet above sea-level.

In the course of geological work some years ago at the mining centres of Goongarrie and Comet Vale, the writer made a sketch survey of the lake, the map of which has been published on a reduced scale in this journal in connection with a paper (1) by the writer on various physiographic phenomena observed during the course of the survey and is here reproduced. The same map, but on a larger scale, appears in an official report (2, Plate I.) by the writer, published by the Geological Survey of Western Australia.

In addition to the phenomena described in the paper (1) just referred to, certain rocks, some *in situ* and some fragmentary, were observed to be pitted, grooved or undermined in a remarkable manner, and under conditions with regard to adjacent rocks



Sketch Map of Lake Goongarrie

that indicated that the forces responsible for the production of such features were working in a peculiarly restricted way. A description of such occurrences, together with a discussion as to the origin of such features, is therefore of interest; but this interest is heightened by the possibility that light may thereby be thrown upon the origin of the surface features of the interior of Western Australia, concerning which—especially in regard to the "dry" lakes or playas—no unanimity has yet been reached. This paper is therefore submitted.

II. Previous Literature.

The writer is not aware of any similar phenomena in Western Australia having been described, and he consequently believes that this paper contains the first description of such phenomena occurring in that State, or indeed in any other part of Australia; but the literature of the other States, which may bear on the matter, has not been searched.

Extra-Australian literature treats of some related occurrences, and such will be referred to below.

III. Climatic Conditions.

In order that the facts and arguments submitted may be better appreciated, a brief statement of the climatic conditions of the area is advisable.

The Comet Vale-Goongarrie district has an average rainfall of about ten inches per annum, most of which falls in fairly steady rain during the winter months. In summer, the individual falls are frequently heavier than those of winter, and consequently are probably responsible for more erosion than the winter rains, notwithstanding the greater abundance of the latter. There is great variation in the annual quantity of rain, some years being as low as four or five inches, whilst a wet year may have up to 19 or 20 inches, which, however, is exceptional.

The range of temperature is considerable. In the summer the temperature may frequently rise above 100°F., and in the winter it may fall below 50°F. in the daytime and may reach freezing point at night. In the summer there is great radiation of heat at night, which thus often brings about a pronounced fall in the temperature during that time. The nights are therefore almost always cool.

The humidity is low, but the evaporation of water is enormous, as is shown by the records from Coolgardie, farther south, where the amount reaches 87 inches annually.

Frosts occur in the winter, and hence are responsible for a certain amount of rock splitting. The variation in day and night temperatures also brings about exfoliation of the rocks.

From the writer's observations, the winds, taken as a whole, are not very strong, except the westerlies, which at times blow with great force, and are apparently the dominant winds.

The lake floor is almost always free from water; hence the name "dry" lake. When rain falls it spreads as a sheet a few inches thick over the lake floor, but it rapidly evaporates. This floor is destitute of vegetation, but at its margin, in those places where the ground is but slightly higher, samphire and other salt-loving vegetation grow, whilst the rest of the country carries small trees and shrubs, forming a scrub, with much bare ground between the plants.

IV. Description of the Occurrences.

(A) Grooved Rocks.

(*a*) "*Greenstones.*"—The western side of Lake Goongarrie at Comet Vale consists, in places, of moderately high and steep cliffs of tough, fine-grained basic rocks ("greenstones"), of which amphibolites are probably predominant. At the immediate foot of the cliffs there is a rock floor of similar rocks.

Just south of a large "natural quarry," almost due east of the old Sand Prince Lease,[1] a remarkable set of grooves may be observed in the lowest rocks of the cliff face. These grooves are closely spaced, are usually in straight lines, and run in all directions in a horizontal plane, in that plane in some cases being roughly parallel to and in other cases intersecting one another; but their inclination to that plane is generally vertical or close to the vertical. They may vary from an inch or two to about ten inches in length, with a depth varying from a few lines to about four inches, and a maximum width of an inch. In length, depth and width, the grooves tend to taper into the solid rock.

On careful examination, these rectilinear grooves are found to follow the small irregular divisional planes (due to jointing and earth movements) which abundantly traverse the rocks, but the grooves are not mere openings in the rocks caused by the two sides of a divisional plane becoming forced apart. The rock material has been actually removed by some natural agent so as to leave a distinct groove of the kind indicated. The grooving agent has merely selected the divisional planes as convenient lines for the commencement of operations. Possibly, without such planes the action would not take place, at least not in such a rectilinear fashion. The grooved surfaces are mostly fairly smooth, but they are not polished.

The grooved rocks extend from three to four feet upwards from the lake floor. Above this height grooves are absent, although the rocks form part of the same rock mass as the grooved ones and have the same divisional planes.

1.—This and other leases referred to below are marked on the geological maps accompanying the writer's geological report on the district (2).

Apart from the grooving, the rocks of the cliff face are breaking down under the influenee of the weather in the usual way.

The accompanying photograph (Pl. XII., Fig. 1) illustrates the features described.

Grooves in greenstones have also been noted at the following localities, among others:—

(i.) At the large "natural quarry" already referred to, there is a talus of fallen bloeks of the fine-grained greenstone, which are grooved for a few feet in height at the base of the talus; whilst the higher blocks are free from grooves.

(ii.) On the western shore of the lake, about four miles north of Goongarrie, at the north-western side of a small "inlet," elose to the railway line, grooving occurs in a rock cliff of greenstone, and is there limited to a height of about two feet from the base, where there is also an abundance of fine sand.

(iii.) Grooves occur in fragments of greenstone lying on the surface of the ground at the foot of the cliffs of the same rock to the west of the lake and about a quarter of a mile north of the old Beelzebub Lease, which is situated about one and a half miles to the east of the Goongarrie railway station. The ground here is well above the level of the lake floor. Fine quartz sand occurs in the grooves.

(iv.) A few chains north of the Lady of the Lake Lease, Goongarrie, there are two small greenstone knobs, not exceeding eight feet in height, the surfaces of which largely consist of fragments of the rock, the result of breaking down by the weather. These fragments for a height of not more than two feet from the floor of the knobs are grooved and also pitted. Above this height grooving and pitting do not occur. There is an abundance of fine-grained quartz sand at the bases of the knobs, and also associated with the grooved and pitted rock fragments.

(v.) On the western shore of the lake at Comet Vale, near a small "inlet" just to the north of the old Planet Lease, there is a greenstone knob a few feet in diameter and about eight feet high. The rocks of the knob are grooved to a height of about four feet from the floor of the knob, being higher than usually noticed elsewhere. On the western side of the knob there is a sand dune higher than the knob, which had wind-blown sand scattered around its base and over its flanks to a height of about five feet. At the time of observation the fine sand at the foot of the knob was being rapidly removed by the wind, and blown against the hard rocks of the knob.

(vi.) In the Black Diamond Lease at the southern end of the Goongarrie mining field, a short watercourse, commencing at a high quartz "blow," ends in a small alluvial fan, on the surface of which are many greenstone fragments, mostly a few inches only in length and breadth. On the alluvial fan there is scarcely any vegetation, and the ground is consequently exposed to the full force of the wind. The rock fragments on the fan are grooved

and also pitted. The country rises from the fan, and concurrently the vegetation increases, but as it does so, the rock fragments cease to be grooved and pitted. In the actual channel of the watercourse the rock fragments have neither grooves nor pits.

(vii.) On the western shore of the lake, probably at Comet Vale, but the exact locality cannot now be indicated, grooving at the base of the greenstone rocks occurs, and some of the grooves are in parallel lines, being evidently along planes of schistosity in the rocks.

In none of the above instances have the rocks been polished.

In addition to the general grooving of rock masses and irregularly shaped fragments noticed above, an interesting occurrence of grooved rocks may now be described. The phenomena have been observed in one locality only, which is on the western side of the lake at Comet Vale near the grooved rocks first described in this paper.

At this point, on the floor of the lake close to the greenstone cliffs, a number of pebbles of the fine-grained greenstone, possessing distinct horizontal grooves, were observed. The pebbles are numerous, but are confined to a small area. They rest on the lake floor by a fairly flat bottom, but otherwise are generally rounded and usually from one to two inches in diameter. The grooving, practically in all pebbles, commences about a quarter of an inch above the bottom of the pebble, and extends, as a rule, completely around each pebble. The grooves are about half an inch in width, and penetrate the rock to a depth of usually less than a quarter of an inch. The surface of the grooved portions of the rock is even, but only slightly smoother than the surrounding parts of the pebble, and there is no indication of polishing. The pebbles have apparently been quite undisturbed for a considerable time.

(*b*) *Quartz and Jasperoid Rocks.*—At the northern end of Lake Goongarrie there is a prominent hill bordering the lake known as "Poverty Hill" (see text-fig. 1). On account of the toughness of the rocks (quartz in the form of reefs and jasperoid banded rocks, the origin of which has not been investigated) composing this hill, the latter projects somewhat into the lake as a distinct point, and hence this feature is known as "Poverty Point." At the foot of the steep cliff forming Poverty Point there is a flat cone of detritus derived from the rocks of Poverty Hill. This cone rises not more than two feet above the lake floor and in length is about one chain from north to south and two chains from east to west.

Boulders and pebbles of the quartz and jasperoid rocks (of many sizes from an inch to 12 inches approximately) are strewn upon the surface of the cone, and many of them are thin flat-lying fragments. All are more or less rounded and smoothed (but not polished) on their sides and upper surfaces, especially in the case

of the larger fragments. These boulders and pebbles are remarkable for the grooving they have sustained. Some of them have pronounced horizontal grooves completely around them; in others the grooves do not extend so far. Generally speaking, the grooving is much stronger in or entirely limited to those portions which have apparently been particularly exposed to the eroding agents. In the jasperoids, when the bands are not parallel to the surface of the ground, the grooves often follow the bands, and therefore may be at any angle.[2] Two horizontal grooves, one above the other, may occur.

The width and depth of the grooves rarely exceed half an inch and are frequently less. The grooves commence usually about a quarter of an inch from the base of the pebbles, but in some cases they were as high as an inch above the base.

In addition to the rounding and grooving, the rocks were also markedly pitted. The pits may be round, elliptical or oval at their mouths and may be drilled at almost any angle from the vertical to the horizontal. In size the pits vary from about two inches to a quarter of an inch or less in diameter. The pits in places unite to form a groove, and, in some instances, the pit has extended into a hole bored right through the pebble.

The grooves and pits and the rounded faces occur, not only in the loose rocks on the small alluvial cone, but also in the rocks forming the base of the cliff. Above a height of about three feet from the floor of the cone, the rocks are almost invariably quite angular, not grooved and not pitted, although some grooving and pitting can be traced to a height of about 25 feet. But where such occurs the cliff is exposed to the action of strong south-westerly, southerly and south-easterly winds.

Similar quartz and jasperoid rocks occur at the Causeway Hill (see text-fig. 1), and there the same phenomena of rounding, grooving and pitting occur as at Poverty Point, to a height, as a rule, of about three feet from the floor of the lake.

At "The Snout" (see text-fig. 1) similar jasperoid rocks are grooved and pitted at the base of the cliff, and also on a shoulder perhaps 20 feet or more above the lake floor, but no details are available.

(B) Pitted Rocks.

(*a*) *Greenstones.*—In various places on the flats, which in part border the western shore of the lake at Goongarrie, there are a number of small, roughly circular knobs of resistant, fairly coarse-grained greenstones, in which felspar and fibrous hornblende are quite prominent. These knobs are usually from about 6 to 15 feet in height, and from about 5 to 12 feet in diameter. The flats on which they rest are usually open spaces,

2.—In the same rocks the evident difference in texture in the component bands brings about differential grooving.

with only a few scattered, low, shrubby plants. The ground may be covered with much white quartz rubble or by sandy or clayey soils.

The rocks of some of the knobs are pitted to a height of about three feet above the surface of the ground. The pits at their openings mostly are circular, with a diameter of usually less than half an inch, and with varying depths, which probably as a rule do not exceed half an inch. The pits penetrate the rocks at different angles, and in places are numerous. They pass alike through the hornblende and felspar, but the hornblende is slightly more resistant to this mode of erosion than the felspar, since in places the hornblende projects as unreduced fragments into the pit, a fact which was not observed in the felspar.

Above the limit in height mentioned, pits are absent, although the upper portions of the rocks are as much exposed to the action of the weather as the lower.[3]

Where pitting occurs, there is generally some fine quartz sand about the base of the knob and in the pits.

It may be noted that in a hornblende felspar porphyry (the precise locality of which cannot now be given) the hornblende was in small spherical nests of about equal size. In the lower portion of the outcrop, the hornblende weathers out more rapidly than the felspar phenocrysts, and hence a number of small pits of uniform size have developed.

The pitting of the greenstones in manner described above may be observed at the following localities:—Towards the northern end of the Bushman Lease, south-east from Goongarrie township; in or near the Lady of the Lake Lease, at the southern end of the Goongarrie field; in the Lord Nelson Lease, just to the west of the Lady of the Lake Lease; and north of the Overlander Lease, which is to the north of the township of Goongarrie.

In addition to the small knobs just referred to, small fragments of greenstone lying on the surface of the ground in certain areas, are also extensively pitted.

The surface of portions of the low-lying, gently-sloping ground, bordering the western shore of the lake at Goongarrie has an abundance of rock fragments of various sizes. The vegetation is sparse, and the fragments, which consist of white quartz and fine and coarse-grained greenstones, are consequently much exposed to wind, sun and rain. It is in the coarse-grained greenstones that pitting, in association with grooving, occurs. Many of the fragments are thin in proportion to their length and breadth, and lie flat. This fact, combined with the gentle slope of the ground, makes the gravitational travelling of the rock fragments very slow; hence many may remain in the same positions for long periods, thus giving erosion an opportunity to make its mark in any particular manner.

3.—A few small pits may be observed on the tops of some greenstone ridges and knobs, but these are clearly due to the action of rain, and they have no relation to the pits of which this paper specially treats.

The pits usually are circular, and may occur on both the top and sides of the rock. On the top, the pits vary in diameter from about one-eighth of an inch to half an inch or more, with similar depths, whilst in some thin fragments the holes have been drilled through from top to bottom. On the sides, the holes do not exceed half an inch in diameter and depth, and are usually much less. Frequently the pits coalesce, and so a more or less continuous horizontal groove may be formed. Fine sand occurs in some of the pits, the surfaces of which are usually fairly smooth.

Localities where the phenomena described may be seen are on the western side of the Golden Sun Lease, Goongarrie; at the small alluvial fan in the Black Diamond Lease, at the southern end of the Goongarrie mining field, referred to under the grooving of greenstones; and generally in various places on the low-lying exposed ground immediately to the west of the lake at both Goongarrie and (more rarely) Comet Vale.

The rocks are nowhere polished.

(*b*) *Quartz and Jasperoid Rocks.*—The pitting of these rocks at Poverty Point and Causeway Hill has been described above when giving details of their grooving.

(*c*) *Other Rocks.*—At the western end of one of the southern arms of the lake, which the writer has named the "Tombstone Arm," a cliff a few feet high occurs, surmounted by a number of projecting but discontinuous rocks of approximately even size. They resemble a number of tombstones, somewhat tilted from the vertical; hence the name, "The Tombstones," given to the locality. These slab-like rocks have had their shape determined by their vertical planes, and by the removal of intervening slabs, but it is not apparent why such a peculiarly selective mode of erosion has taken place.

The component rocks are believed to be fine-grained quartz-porphyries, but the writer's records on this point are incomplete. The surface of a "tombstone" is coated with a film of iron oxide, and is free from pits and grooves.

The rocks which form the low cliff referred to are dark grey shales and slates from which masses several feet in length have been detached. The upper surfaces and sides of these detached blocks often have pits varying in diameter from a quarter of an inch to about one foot, and in depth from a quarter of an inch to three inches. They are usually roughly circular in surface outline, except where two or more pits have coalesced into one elongated one. The pits may be large shallow saucer-like hollows or relatively deep narrow ones, or they may have about the same surface diameter and depth.

At a tiny gully close to "The Tombstones," there is a short, sharp drop to a lower level, down which rain water occasionally falls. The rocks at this point are much pitted, and of especial interest is a concretionary structure which has facilitated the hollowing out of the rocks on vertical faces in a remarkable manner.

The writer's records unfortunately are insufficient to state what these concretionary rocks are.

The shales and slates at "The Tombstones" are mostly free from the iron oxide film mentioned above.

(C) Miniature Pedestal[4] Rocks.

On the western shore of the lake at Comet Vale, and quite close to the rocky cliffs, several examples of miniature pedestal rocks occur. The lake floor at the edge of the lake is a "billiard-table" rock floor. The pedestal rocks are part of the same rock mass as the floor, and consist of fine-grained greenstones of the type already referred to. They are so tough that examples of the pedestal rocks could only be obtained by the writer by wedging them out from the floor along the close-set and irregular joint planes of the rocks.

Kirk Bryan (4. p. 123) describes a pedestal rock as an isolated rock consisting of a larger mass above, supported on a more slender pedestal.

These miniature pedestal rocks attain a height of two to three inches above the rock floor. In horizontal section, the portions above the pedestals are roughly circular or oval, with diameters up to about two inches; and they project about half an inch or more beyond the pedestals, but the extent of the projection varies in the same pedestal rock and in different rocks. The pedestals themselves form short columns about one inch, and less, in height. The result is the well-known mushroom appearance. The surface of the pedestals and of the rock floor overhung by the upper masses is smoothed by abrasion, but is not polished.

At Poverty Point, some of the quartz or jasperoid rock fragments on the surface of the alluvial cone mentioned above, have been undermined so as to form miniature pedestal rocks with a pedestal about an inch in height, and a top that may be six or seven inches in diameter, and which may project one to two inches beyond the pedestal. The rock fragments are smoothed and rounded.

The pedestal rocks described are in miniature only, but nevertheless they are of interest, inasmuch as they indicate, to some extent, the nature of the erosion processes operating in the district.

V. The Origin of the described Phenomena.

For the sake of clearness and convenience of reference, the various types of erosion dealt with in this paper have been separately described. In considering, however, the possible origin of

4.—The word "pedestal" has been suggested by Kirk Bryan (3, 4, and 5) as a descriptive term for the kind of rocks now described, and is preferable, in the writer's opinion, to the old term "mushroom."

the described features, it is convenient to treat the subject as a whole, touching on the various aspects as they arise.

In the following discussion the semi-arid nature of the country, with the resulting scarcity or absence of vegetation, and the abundance of blown sand available must be borne in mind. The mode of occurrence of the sand is described in publications (1) and (6).

As regards the agents of erosion which have brought about the effects noted, the abrasive action of streams, lakes and seas, and of the wind; the action of rain in its mechanical and chemical aspects; the effect of the crystallization of salts at the surface of the rocks; and differential atmospheric weathering generally, must be considered. There may, of course, be a combination of forces.

No satisfactory evidence has yet been adduced to show that the sea has had any influence in moulding the rock cliffs and rock floors of the lake. The former occurrence of large freshwater lakes in the interior of Western Australia has been postulated, but definite evidence is as yet wanting. Even if the sea had recently occupied large areas of the country, or if lakes of the type just mentioned had previously existed, all the effects noted could not be ascribed to such agencies, which may therefore be disregarded.

Again, the erosive power of the very shallow waters that occasionally cover the lake surface is too weak to produce the various kinds of grooving and pitting, or the pedestal rocks described above. Moreover, some of the features observed occur beyond, although close to the lake, so that there must be some agent more general in its action than sea or lake waters.

Rain, chiefly by its chemical action, may form pits in rocks containing much soluble material, such as arenaceous limestones; but such pitting, so far as the writer is aware, is rare in igneous and most sedimentary rocks. Rain, no doubt, in its combined chemical and mechanical action, can groove and pit rocks, but such action would not be limited to a definite height above the surface of the ground. In the examples described in this paper (omitting the rocks at "The Tombstones"), there is such a limitation on the cliff faces, except in occasional special cases, which can be accounted for. Similarly, pitting and grooving are only found among surface rock fragments where the ground is open and largely destitute of vegetation, and therefore exposed to the action of the wind.

Rain, therefore, does not appear to be the primary cause of the pits and grooves, although, once erosion had commenced, it would doubtless be hastened by the rain; but this would hardly or only slightly apply to horizontal pits and grooves.

The effects of the crystallization of salts must be considered. The water beneath the floor of the lake is heavily charged with common salt, and much of the underground water at some distance from the western shore of the lake also contains the same substance in abundance. Other salts also occur.

If crystallization takes place when the water rises by capillary attraction to the surface and there evaporates, the rocks may be disintegrated to some extent, as the writer in an earlier paper (7) has indicated.

Where pronounced divisional planes occur in the face of a cliff (as in the fine-grained greenstone cliffs containing at their base the rectilinear grooves described above) these planes may possibly facilitate the ascension of the salt-charged water through the immediately adjacent areas of the rock; and at the surface, as a result of the crystallization of the salt, slight disintegration or internal strain may occur. If wind-driven sand be the chief cause of the grooves, it would be aided by such disintegration or strain.

The crystallization of salt at Lake Goongarrie cliffs, however, seems to cause an irregular undermining by a flaking of the rock rather than disruption or strain along the divisional planes. Where grooves are several inches deep, it is improbable that they are caused wholly or largely by salt crystallization, as it is difficult to imagine the process working in this regular way. Moreover, the grooved rocks forming the actual cliff face have mostly been broken away from the main mass—apparently before the grooves were formed—and consequently evaporation of the water and precipitation of the included salts would doubtless take place at the surface of the rocks *in situ*.

So far as the writer's observations and recollections go, no disruption or weakening along the division planes occurs. The surface of the grooved rocks is firm, and free from signs of disintegration by flaking or crumbling.

With regard to the pits in the small coarse-grained greenstone knobs, the crystallization of salt may perhaps loosen or detach a mineral fragment, and so be the means of starting a pit; but it is inconceivable that the process should so continue as to form the spherical fairly smooth pits already described. Rather there would be a disintegration over practically the whole of the surface of the area affected. Furthermore, these pitted rocks consist in part of blocks detached from the main mass, and it is a fair assumption that the pits have developed since the detachment—at least in some of the rocks. If so, the crystallization of salts is not likely to occur on the surface of the fragmentary rocks.

With reference to the horizontal grooving of the fragments of quartz, greenstone and other rocks lying loose upon the surface of and, consequently, not in continuous contact with the ground, the same difficulty as to the passage of the capillary water into the fragments again occurs. If, however, this difficulty were overcome, the crystallization of salts at an even height above the surface of the ground seems improbable. Crystallization is more likely to occur over the whole exposed surface. Apart, however, from theoretical considerations, the rock fragments show no evidence of decay through crystallization of salts.

Other chemical action will tend to weaken the coherence of the rocks, and so make them more easily eroded by any eroding agent.

There is no indication that temperature variation is the cause of the pits and grooves or that it has aided in their formation.

The abrasive action of the wind being the remaining possible factor, is therefore apparently the prime cause of the pits and grooves. Its action is discussed below.

At "The Tombstones" the majority of the pits clearly appear to be due chiefly to the solvent action of rain. This conclusion is suggested by the fact that there is no definite limitation of the height at which they occur, and by the large, shallow, saucer-shaped character of many of the pits. The process appears to start with the formation of small irregular hollows (due to differential atmospheric erosion) on the surfaces of the rocks. Rain water collects in these hollows and acts as a slight solvent, thus further disintegrating the rocks. Further rain will wash out the separated material, and, the processes being repeated, the cavities become enlarged. Some of the smaller pits, and especially the more or less horizontal ones, may be due to the action of the wind. The hollowing out of the rocks at the small waterfall is due mainly to the fall and splash of the water.

Kirk Bryan in various publications (3, 4 and 5) has given instances of pedestal rocks formed otherwise than by wind action. He considers (3, p. 11) their formation to be due to the work of rain, of mechanical disruption, of stream action and of chemical weathering; and he has shown (3 and 5) in lucid and convincing fashion that in arid areas, in some instances, such rocks are moulded into their present shapes by the action of a "drip curtain" during rain, and by the spreading of a film of water on the under surface of the overhanging rock. Pedestal rock formation takes place in this way, especially when a less resistant rock, e.g., a shale, underlies a more resistant one, e.g., a conglomerate. In the case, however, of the miniature pedestal rocks on the floor of Lake Goongarrie, the homogeneous character of the rocks, the smoothness of the face of the pedestal and of the floor forming its base, the absence of the grooves caused by the drip curtain, and the weakness as an eroding agent of such a tiny drip curtain, if formed, suggest strongly that rain action must be eliminated.

The mode of occurrence of the miniature pedestal rocks, where those rocks are *in situ*, should be favourable to erosion by salt crystallization, as it is in undermined areas that one would expect such crystallization to take place. No such effects, however, are visible megascopically. The surface of the pedestal is smooth and free from any indication of crumbling or flaking; and apparently the pedestal is as tough as the rock above and below. If crystallization is taking place, then its action appears to be very slight, or even negligible.

Microscopical examination of the miniature pedestal rocks —as well as of the pitted and grooved rocks—might throw some light on the question whether salt crystallization has directly or indirectly aided in the formation of the pits, grooves and pedestal rocks.

The remarks made above in connection with the pits and grooves as to further chemical action and the effect of temperature variation apply to the miniature pedestal rocks.

The wind in its abrasive capacity therefore appears to be the principal agent in the formation of the pedestal rocks.

By a process of elimination of other possible factors the writer has arrived at the conclusion that the wind in its direct abrasive capacity is the chief agent in the production of most of the unique features described in this paper; and the general conditions prevailing favour this view. These conditions are · limitation in height of erosion, which is especially characteristic of wind action; the dry climate; the sparse vegetation; and the abundance of quartz sand. In the case of the pits in the coarse-grained greenstones, Harger's suggestion (7, p. xxxv) with regard to the honeycombing of "augen" gneiss, that the holes were probably started by the weathering out of a particular mineral, would probably apply.

The actual mode in which wind-driven sand brings about the results stated may now be considered, although the subject is a difficult one on account of want of direct observation of the process.

The restriction of the grooves in the cliffs and of the pits in the small coarse-grained greenstone knobs to a height of about three feet above the surface of the ground is probably due—at least in part—to the wind being unable, as a rule, to lift above this height particles of sand of a size or in numbers sufficient to erode a rock surface. This limitation is apparently of wide application. Kirk Bryan (5, p. 12) states that all authorities are agreed that two to three feet above the ground surface is the limit of effective wind scour; and he refers to the paper by W. H. Hobbs, who shows (9, p. 33), among other examples, that in the Great Oasis of the Libyan Desert the cast-iron telegraph poles lining the railway were well burnished by the flying sand to a height above the ground of only about a yard (see also p. 35). Hobbs's observations are strikingly confirmed by the records given in this paper, if wind-driven sand has caused the grooves and pits.

The actual process is difficult to visualize, but the following suggestions are made. The more or less vertical grooves will be first discussed. The sand must be lifted and driven against and perhaps up or down the face of the rocks to the height mentioned. Erosion may take place by this means, but so comparatively evenly —except in specially favourable places—that there is no definite record of the work of the sand blast. The "frosting" evenly over the surface of glass by the sand blast in Nature is an illus-

tration of this widespread erosion. It is easily recognized on the glass on account of the smooth surface of the glass at the commencement of the bombardment of the sand grains, and the resulting roughening of such surface. In rocks, however, such as greenstones, the surface would show little recognizable change, unless the action were very strong, and except, as already noted, in specially favourable places, such as joint or division planes. These provide lines of weakness along which the wind-driven grains may erode faster than the adjacent portions of the rock. In this way a slight groove may be made, which then supplies a definite passage along which the rasping sand grains may be pushed up or down by the wind, which must be assumed, when it approaches the rock face, to be deflected in various ways. So the grooves may deepen, widen and lengthen, and are probably most pronounced close to the ground.

The typical pits on the faces of masses of rock rising well above the surface of the ground are in the coarse-grained greenstone knobs. The formation of the pits in these rocks is no doubt favoured by the comparatively large crystals of felspar and hornblende, of which the rocks are chiefly composed. Bombardment by wind-driven quartz grains, to a height of about three feet above the surface of the ground, takes place, and if, owing to ordinary atmospheric weathering or crystallization of salt, a piece of felspar or hornblende has been detached, a small hollow or incipient pit in the rock face will result. Sand grains are thrown against the rock face to the height mentioned, and some must enter the pit. Centrifugal action as suggested by Harger (8, p. xxxv), may be set up, whereby the sand grains are whirled round the walls of the cavity, thereby increasing its size.

Regarding the horizontal grooving of loose fragments of rocks and to the undermining that takes place in the formation of the miniature pedestal rocks, the grooves usually commence about one-quarter to one-half of an inch above the base of the fragment, although it has been shown in this paper that where bands of varying degrees of toughness occur, and even in apparently quite homogeneous quartz, there may be two horizontal grooves, one above the other. The undermining of the pedestal rock is also just above the surface of the ground. The difficulty is to understand why the groove is formed so uniformly at the height mentioned, and not only in one kind of rock, but also in several classes.

Long and patient work would be necessary to determine this question by actual observation; but if it be accepted, owing to the elimination of all other possible agents as prime factors, that wind-driven sand is the cause, then it must be assumed that such sand, owing to the quantity available, or to its coarseness of grain, or to the strength of the wind itself at the height mentioned, or all or some of these combined, acts most powerfully at that height. The sand must act above this height, but apparently so evenly that it shows no striking effects.

Harger (8, p. xxxiv) states that in late German South-West Africa the cutting or eroding action of the sand-laden blast is the most severe just above the ground level, the heavier grains of sand acting like a rasp and in time cutting upstanding pillars of rock right through, an example in granite being given. Another result is the formation of "mushroom-topped" tors. Harger's observations are thus in accord with those recorded in this paper.

The writer's observations do not show that pits and grooves occur more frequently on one side of an outcrop than on another, except in one or two instances where they are more numerous on the eastern than on the western side.

The dominant winds appear to be westerly, but these may not be the prevailing winds. The wind, however, probably forms eddies in the vicinity of rock masses. See Hobbs (9, pp. 35 et seq.) and Harger (8, p. xxxv), who states that the best and deepest honeycombing is seen on the lee side of the rock masses.

In support of the wind theory, reference may be made to the outcrops of a vertically banded siliceous ironstone about 10 to 12 inches thick, occurring at Goongarrie to the west of the lake. These outcrops form a band at the junction of two other rocks, and they may be traced in a north-north-westerly direction intermittently for some miles. This band projects, on the average, for about 12 inches above the surface of the surrounding ground. Its surface is grooved, pitted, smoothed and rounded, and presents a striking contrast with the sharp contours of similar rocks elsewhere in the district, but situated under different conditions. The bare surrounding ground and the abundance of fine quartz sand in the vicinity leave little doubt that the wind is responsible for the features described.

If the conclusions set out in this paper as to wind erosion, and particularly with regard to the miniature pedestal rocks, be well founded, they are important in that they support the idea that the rock floor of the lake on its western shore is due to wind planation.

The writer has in another publication (10) pointed out that the mode of rounding described in that paper of fine-grained greenstone pebbles does not take place until the iron oxide crust, which is very widespread, has been broken. In the same group of rocks, pitting and grooving do not occur, usually, unless this iron crust is absent. The facts that the fine-grained greenstones from which the crust has always been absent or from which it has been removed after its formation, and that the pitting and grooving of these greenstones occur generally at the base of cliffs, are coincidences merely, since the coarse-grained greenstones and the quartz and jasperoid rocks may be without a distinctive iron crust at any height, but the pitting and grooving are restricted as shown in this paper.

At "The Tombstones," the sedimentary rocks are free from the iron crust, and pits abound in them, but as shown above, they are, in the main, essentially solution hollows. In the adjacent

rocks (probably porphyries), which project well above the surface of the ground as "tombstones," an iron crust is well developed, and pitting is absent. Thus in those two groups of rocks we have striking examples of how erosion may be retarded or hastened according to the occurrence or non-occurrence of the protective iron crust.

The relations between the crust-bearing and the crustless rocks, especially those of the same kind, would probably repay close investigation.

VI. Records of Grooving and Pitting elsewhere by Wind Action.

That pitting and grooving of rock surfaces have in some instances has been caused by the action of the wind has been stated by various writers. The following remarks summarize practically all records that have come under the writer's notice. He is indebted to Mr. Kirk Bryan, of the United States Geological Survey, for several of the references.

T. O. Bosworth (11) describes small corrugations and pits in granite, due to erosion by wind-blown sand, on the coast of Mull, Scotland. The quartz and felspar in the rock have been highly polished by this action.

W. P. Blake (12) describes the cutting by the sand blast of a granite surface into " long and perfectly parallel grooves and little furrows " on a mountain pass in California. The rocks were also smoothed and polished by the action of the wind.

R. F. Rand (13) states that at Angra Pequena, on the south-west African coast, biotite schist and granite have suffered great pitting and honeycombing by the action of the wind, which is very powerful and blows from the coast.

A. Wade (14) points out that the softer limestones of the Eastern Desert of Egypt are sometimes regularly grooved by the wind in such a manner as often to simulate bedding planes. Andesites and porphyries are also grooved all over in a peculiar manner by the action of wind-blown sand.

R. D. Oldham (15) describes grooves of varying size in quartzites and sandstones caused by wind erosion.

R. W. G. Hingston (16) records the erosive action of the wind in a gorge in Tibet. Granite boulders on their windward side were polished, and were cut into by deep pits and grooves, some of the latter an inch in depth.

E. de Martonne (17, pp. 663, 664) briefly refers to the disintegration of heterogeneous rocks, such as sandstones, conglomerates and granites. Grains become detached and are swept away by the wind. This results in the formation of a honeycombed surface. The pits may be enlarged by wind corrasion until potholes result, such potholes being common in granites (17, p. 668).

Johannes Walther (18, p. 168 and fig. 132, p. 169) describes the well-known "stone lattice" of the desert.

H. S. Harger (8, p. xxxv and fig. 7) describes the occurrence of "augen" gneiss in the late German south-west Africa, where the rock has been extensively honeycombed by the corrasive action of wind and weather. He points out that the best and deepest honeycombing is seen on the lee side of the rock masses, and that the holes, which were probably started by the weathering away or falling out of a particular mineral, have been rounded and enlarged by loose grit being whirled by the wind around the walls of the cavities.

VII. Summary.

At Lake Goongarrie, a playa in sub-arid Western Australia, the conditions are described under which certain rocks are being grooved and pitted, and others undermined so as to form miniature pedestal rocks.

The rocks concerned are "greenstones," quartz, certain jasperoid rocks, and shales. They occur as rocky cliffs of the lake; as small isolated rocky knobs; and as fragments scattered over portions of the surface of the lake floor on the western shore, and over the adjacent wind-exposed, low-lying ground, which has but scanty vegetation.

These rocks are pitted and grooved. The grooves may run at all angles in a horizontal plane, although in their inclination to that plane tending generally towards the vertical, and, where this occurs, the irregularities are due to the numerous small joints and other division planes by which the rocks are traversed. Other grooves are horizontal. The pits are mostly small, but they are in some cases of moderate size.

Where the rocks occur as cliffs or knobs, the grooving and pitting (except the pits at the locality known as "The Tombstones") are restricted to a height of about three feet from the base of the cliff or of the knob, as the case may be; and where they occur as surface fragments, the grooving and pitting are restricted to those fragments which lie on nearly flat wind-exposed areas with scanty vegetation.

The miniature pedestal rocks are of the fine-grained greenstone class, and occur on the western shore of the lake close to the cliffs of the same rocks, which there bound the lake.

From a consideration of the mode of occurrence of the grooves and pits and of the tiny pedestal rocks, water, both in its mechanical and solvent action, is eliminated as the chief agent in the production of the phenomena described. The disruptive power of salts brought by capillary attraction to the surface, and there crystallizing, is also practically eliminated; and the wind, acting in its abrasive capacity, is regarded as the predominant factor. This, however, does not apply to the pits at "The Tombstones," where

water, in its solvent action, is considered to be the chief cause of those pits.

A brief account of extra-Australian records of pitting and grooving of rocks is given.

The writer is indebted to Professor Skeats for criticism of this paper.

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EXPLANATION OF PLATES.

Plate XII.

Fig. 1.—Rectilinear grooving in the fine-grained greenstone. Cliff face south of the large "natural quarry" on the western shore of Lake Goongarrie at Comet Vale. Note the absence of grooving towards the top of the figure.

Fig. 2.—Miniature pedestal rock of fine-grained greenstone on the floor of the western shore of Lake Goongarrie at Comet Vale, near the large "natural quarry." Slightly less than natural size.

Fig. 3.—Pebbles of the fine-grained greenstone, showing the horizontal groove above the base. From the rock floor of the western shore of Lake Goongarrie at Comet Vale, near the large "natural quarry." Natural size.

Plate XIII.

Fig. 1.—A fragment of the coarse-grained greenstone, showing the almost continuous horizontal groove slightly above the base. Some of the pits on the top can be observed. From west of the Golden Sun Lease, Goongarrie. Natural size.

Fig. 2.—A fragment of quartz with a horizontal groove slightly above the base, particularly shown in profile at each end. From flat cone at the foot of Poverty Point, northern end of Lake Goongarrie, Comet Vale. Natural size.

Fig. 3.—A fragment of jasperoid rock, showing its rounded surface and the deep notch at one end. From near the Lady of the Lake Lease, Goongarrie. Natural size.

ADDENDUM.

A series of papers by the writer treating of various phases of physiography in sub-arid Western Australia appeared in earlier volumes of this Journal. The proofs of most of those papers

Fig. 1

Fig. 2

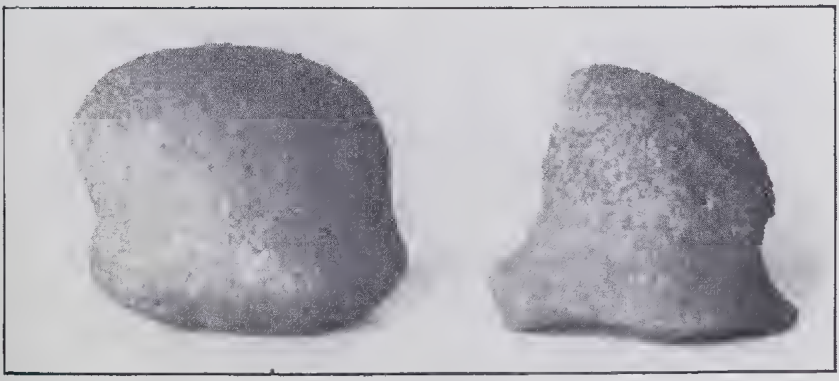

Fig. 3